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A model to examine farm household trade-offs and synergies with an application to smallholders in Vietnam

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ABSTRACT

Farm models have the potential to describe farming systems and livelihoods, identify trade-offs and synergies, and provide *ex-ante* assessments of agricultural technologies and policies. We developed three new modules related to budget, labor, and human nutrition for the bio-economic whole-farm model 'FarmDESIGN'. The expanded model positions the farming enterprise within the farm household. We illustrate the model's new capabilities for farm households in two villages in Northwest Vietnam, where we conducted multi-objective optimization to identify options for improving the farm households' current performance on key sustainability and livelihood indicators. Modeling results suggest trade-offs between environmental, economic, and social objectives are common, although not universal. The new modules increase the scope for modeling flows of resources (namely cash, labor, and food) between the farm enterprise and the farm household, as well as beyond the farm gate. This allows conducting modeling explorations, optimization routines, and scenario analyses in farming systems research.

1. Introduction

Family-run farms are key agents in global food production, particularly those with landholdings ≤50 ha (Graeub et al., 2016; Herrero et al., 2017). In less-developed countries where gains in food production are acutely needed, up to 70% of food calories are produced by farmers with landholdings < 5 ha, who are classified as 'smallholders' (Samberg et al., 2016). Despite their contribution to food production, many of these smallholders are nutritionally vulnerable and score poorly on health indicators related to nutrition and dietary diversity (IFPRI, 2016; Pandey et al., 2016; Pingali, 2015). The paradox that these smallholders play a vital role in global food provisioning while simultaneously falling short of meeting their own nutritional needs grounds the argument that these smallholders should be the primary target of innovations to sustainably increase production, improve diets, and improve livelihoods (IFAD and UNEP, 2013; Tittonell et al., 2016). Increasingly, it is recognized that a household-level approach is needed for the analysis of such innovations[1] (Van Wijk et al., 2014).

For many smallholders, the farm enterprise is tightly intertwined with household dynamics, since these households rely largely on family labor to manage the farm and play dual roles as both producers and consumers of agricultural outputs (Altieri et al., 2012; Stephens et al., 2018). Additionally, daily farm management decisions may be influenced by factors such as resource endowment, gender distribution, and power structures, among others (Michalscheck et al., 2018). These decisions are further shaped by competing farm and household needs across spatial and temporal scales (Rufino et al., 2011; Zingore et al., 2010), and may have radiating impacts on other farm household

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[1] We use the term 'farm household' to distinguish a unit slightly different than a 'farm'. A farm household encompasses a family-run farm enterprise, the household managing it, and any income-earning activities by household members outside the farm. 'Farm' refers to the farming component of the household, i.e. the production of crops and livestock and interactions between production sub-systems. In our study, the 'farm' is viewed as one of the enterprises of the household, where, for example, farm income is one of the household's income sources and farm operations are one of the household's labor sinks.

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concerns. For example, the choice or necessity to pursue off-farm employment activities[2] may play an important role not only in farm household economics but also in farm production and nutritional status (Babatunde and Qaim, 2010; Pfeiffer et al., 2009; Reardon et al., 1998). Similarly, the choice of where to source food for household consumption (from the market, the wild, or from on-farm production) may have implications for both the economic and nutritional status of the farm household (Bellon et al., 2016; Paumgarten et al., 2018; Sibhatu et al., 2015).

In agricultural systems research, whole-farm models have been widely adopted to explore new management options, technologies, and farming systems innovations, and to conduct scenario analyses (Janssen and van Ittersum, 2007; Jones et al., 2017a; Le Gal et al., 2011; Robertson et al., 2012; Thornton and Herrero, 2001). Iterative cycles of model application and improvement are considered necessary to ensure that modeling tools stay relevant within evolving research priorities and societal concerns (Antle et al., 2017; Jones et al., 2017b). Although the development and testing of agricultural technologies and farming systems innovations by researchers often occurs at the field scale, smallholders evaluate them and encounter constraints to their adoption at the farm, household, and market scales (Giller et al., 2011). Moreover, relationships among farm concerns and livelihood options frequently extend beyond the farm enterprise (Frelat et al., 2016; Reardon et al., 2007) and result in trade-offs between farm and household priorities (Klapwijk et al., 2014). As key factors in household decision making, there is scope for improvement to better capture cash and labor constraints within whole-farm models (Kanter et al., 2018). This has already been done in economic models of agricultural systems, for example MIDAS (Kingwell and Pannell, 1987) and utility maximization models that account for leisure (Komarek and Ahmadi-Esfahani, 2011; Singh et al., 1986; Tiberti and Tiberti, 2015).

Our study complements the longstanding literature on whole-farm modeling and responds to the demand for up-to-date modeling tools by embedding cash, labor, and dietary decisions into a bio-economic whole-farm model. We present three new modules[3] which were designed and added to the already-existing FarmDESIGN model (Groot et al., 2012). The new modules (‘Household budget’, ‘Household labor’, and ‘Household nutrition’) were designed to reflect the different roles a farm enterprise can play for a farm household, depending on its production objectives and livelihood strategy (Barrett et al., 2010; Frelat et al., 2016). Earlier versions of FarmDESIGN included budget and labor modules for the farming enterprise, but the conceptual delineation of the farm household was not explicit. This enabled the model to capture profit and labor balances from the farm enterprise only, as factors such as off-farm employment and leisure activities were not accounted for. The expanded model now positions the farming enterprise within the farm household, and includes productive, economic, environmental, social, and nutrition related indicators at the farm–-household level. These changes increase the scope of FarmDESIGN's applicability for modeling farming systems where resources (namely cash, labor, and food) flow between the farm enterprise and the farm household, as well as beyond the farm gate.

In the following section (Section 2) we present the FarmDESIGN model and document the new budget, labor, and nutrition modules. We then introduce two case-study farm households in Northwest Vietnam to which we applied the new model (Section 3). For these farm households, we explored trade-offs and synergies between social, economic, and environmental indicators at the farm–household scale. This was done by executing a multi-objective optimization with the objectives of simultaneously maximizing soil organic matter (OM) balance, household free budget, leisure time, and dietary energy sufficiency. The simulation results from the optimization are presented in Section 4, where we focus on interactions between objectives and household decisions regarding cash and labor allocation. Following is a discussion of how our results connect to earlier studies and provide scope for evaluating the new model (Section 5), and conclusions about both the case study specifically and the applicability of the new model generally (Section 6).

2. Model description

2.1. Previous version of the FarmDESIGN model

FarmDESIGN is a bio-economic whole-farm model developed for the analysis and redesign of mixed crop–livestock farm systems (Groot et al., 2012). It is a static and exploratory model that quantifies the productive, economic, and environmental performance of a farm system on an annual basis (Cortez-Arriola et al., 2016). The model is configured to facilitate the ‘DEED’ research approach to farming systems analysis and scenario evaluation, which follows four consecutive phases (Describe, Explain, Explore, Design) that are meant to be executed in iterative cycles (Giller et al., 2008; Giller et al., 2011).

In the Describe phase, data are used to describe the state of the farm system under study, that is, the model is parameterized according to local conditions. The model quantifies the current performance of the farm system in terms of annual resource flows and balances that are grouped into modules (Explain phase; Fig. 1). For details on how these balances are calculated, see Groot et al. (2012). Farm performance can be evaluated considering various objectives by looking at resource balances as proxy indicators. In the Explore phase, options to adjust farm management to meet specific objectives can be explored through a multi-objective optimization. The objectives and decision variables are selected and configured by the model user, and the optimization involves an evolutionary algorithm which generates a set of alternative farm configurations within given resources and constraints (Groot et al., 2012). The set of alternative farm configurations generated by the model represent a solution space within which solutions can be ranked based on Pareto-optimality (see Groot and Rossing, 2011). Thus, trade-offs and synergies between different production, environmental, and economic objectives may be visualized and analyzed. Finally, feasible alternative farm configurations may be selected and implemented together with farmers or other stakeholders (Design phase). In this study, we forgo the Design phase because our objective was to illustrate the operation of the new modules, and not to simulate interventions or implement the results of modeling exercises.

2.2. New FarmDESIGN modules

We improved FarmDESIGN by including two new entity types: ‘Household’ and ‘Household member’, and three new modules: ‘Household budget’, ‘Household labor’, and ‘Household nutrition’ (Fig. 1). Each farm is associated with a household, and the household can have multiple members. Per household member the model user can specify the age, sex and physiological state (either ‘standard’, or, for women two additional states: ‘pregnant’ or ‘lactating’), which determine the dietary requirements. Moreover, the total stock of time (in hours) can be entered as a parameter for each household member, and it is used to provide an upper bound on the time available for household activities including leisure to be allocated to different uses (see Section 2.2.2).

Earlier work with FarmDESIGN considered *farm operating profit* (defined as the revenue from agricultural activities minus incurred costs) as the main indicator for economic performance, and *farm labor*

[2] In our study, off-farm activities refer to all activities away from one's own property, regardless of sectoral or functional classification (Barrett et al., 2001). These off-farm activities can include working for wages or self-employment and can be in the agriculture or non-agriculture sectors of the economy.

[3] In our study, ‘module’ refers to a sub-component of the full FarmDESIGN model. A module organizes information related to one specific component of the farm household, for example, labor, budget, or nutrition.

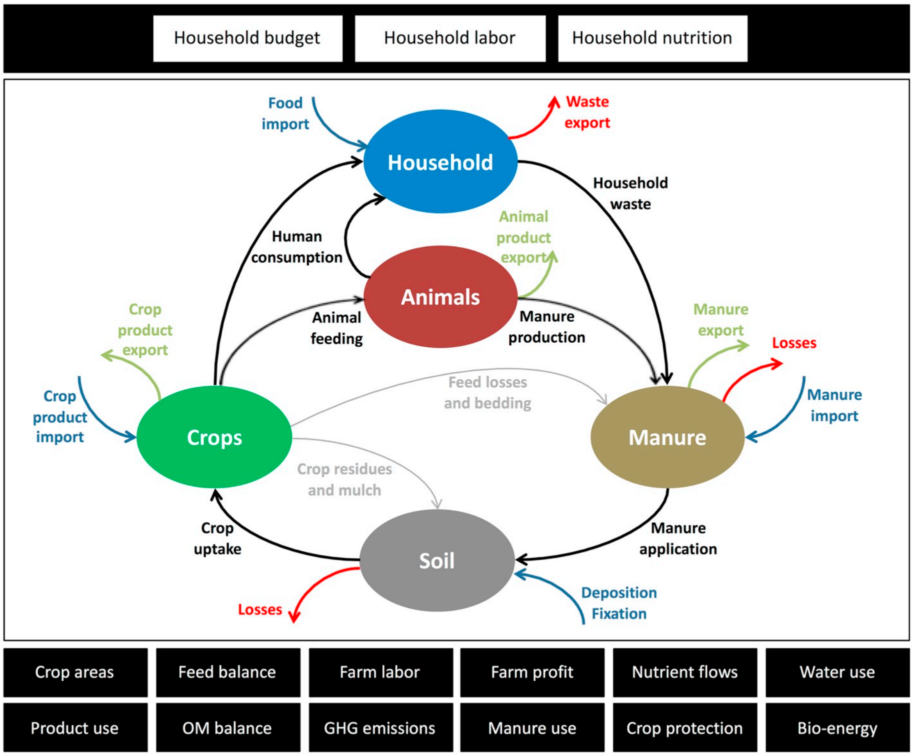

Fig. 1. Schematic representation of the FarmDESIGN model showing farm resource flows, and original modules (black boxes) and new modules (white boxes) added to calculate diverse farm household performance indicators. The black and grey arrows indicate resource flows within the farm–household system. Blue arrows represent inflows, while other arrows denote outflows of products (green) or losses (red). OM = organic matter; GHG = greenhouse gases; "Product use" = allocation of crop and animal products produced on-farm or imported from outside. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

balance (calculated as the difference between the total available labor and the labor required for agricultural activities) as a key social indicator (Cortez-Arriola et al., 2016; Flores-Sanchez et al., 2015; Groot et al., 2012; Mandryk et al., 2014). The new modules expand the scope of FarmDESIGN to conduct multi-objective optimization from the perspective of the farm household, rather than just the farm enterprise. The new 'Household budget' module includes economic indicators for off-farm activities and the value of consumable food, in addition to the total value of on-farm production, to calculate the new economic indicator *household free budget*. The new 'Household labor' module accounts for off-farm work and hired labor, in addition to on-farm work conducted by the farm family, to calculate the new social indicator *leisure time*. In the new 'Household nutrition' module several indicators related to dietary diversity, nutrient adequacy, and dietary patterns were included to assess the diet quality of the household (Groot et al., 2017); the nutrition indicator *dietary energy deviation* is one of them.

2.2.1. 'Household budget' module

The 'Household budget' module is based on the theory of the agricultural household, outlined in Singh et al. (1986), where a specific household maximizes its utility subject to a cash and labor constraint. Eq. (1) was modified from Singh et al. (1986) and captures the cash constraint, which we express in United States dollars (USD) per year:

$$p_m X_m = p_a (Q_a - X_a) - p_w (L - H - F) - p_h H - p_v V + E \qquad (1)$$

In Eq. (1), decision variables include:

- X_m is a vector of quantities of market-purchased goods;
- Q_a is the production of an agricultural staple such as a cereal crop (kg);
- X_a is the quantity consumed of the agricultural staple (kg) (so that Q_a - X_a is its marketed surplus);
- L is total labor input into on-farm activities by the family or by hired-in laborers (hours);
- H is the hired-in laborers for on-farm activities (hours), and is the on-family labor part of L;
- F is total family labor input working on-farm and off-farm (hours);
- V is a vector of variable inputs (for example, fertilizer);
- E is any non-labor, non-farm income (USD).

In Eq. (1), parameters include:

- p_m is a vector of prices for the market-purchased goods (which can include food) (USD per unit of quantity purchased);
- p_a is the price of the agricultural staple (USD kg^{-1});
- p_w is the market wage for labor (USD $hour^{-1}$);
- p_h is the price of hired labor (USD $hour^{-1}$);
- p_v is the variable input's market price (USD per unit of quantity purchased).

The decision variables are presented in Tables A2 and A3 of the Appendix, while parameter values are listed in Table A4. A complete overview of model parameters and settings can be found in the Supplementary material.

In Eq. (1) all decision variables and parameters are non-negative, and the following constraints hold: $(L - H - F) \le 0$ and $H \le L$, and if $(L - H - F) < 0$ then labor time of household members is used for off-farm activities or is spent on leisure (see Section 2.2.2). We further disaggregate L into three labor categories:

- General farm management (e.g. maintenance, trading, and accounting, L_G);
- Crop management (L_C);
- Livestock management (L_A).

Transaction costs in the labor market may mean that for the same agricultural activity, the purchasing price of labor (hired labor wage paid, p_h) may exceed the selling price of labor (off-farm wage earned, p_w), so that $p_h > p_w$. These prices can be specified as model parameters.

The indicator *household free budget* reflects the cash constraint from Eq. (1), which relates to two farm household decisions associated with working time allocation and food choices. First, household members can allocate their income-generating work time to either on- or off-farm activities. This decision will affect the proportion of farm income in the total household income. Second, household members can make decisions around how much of their food is sourced from the market versus produced on-farm. This decision affects the cost of supplying food-based nutrients to the household due to differences between the sale and purchase prices of food. We capture these two decisions in the 'Household budget' module with the addition of three variables, *off-farm income*, *food costs*, and *other expenditures*, which supplement the already-existing variable *operating profit* to make the 'Household budget' module distinct from FarmDESIGN's previous 'Farm profit' module. The primary indicator of interest calculated in the 'Household budget' module is *household free budget* Eq. (2):

$$B_H = (I_F + I_O) - (C_F + C_E) \tag{2}$$

where:

- B_H is *household free budget* (USD year^{-1}). In Eq. (1) there is no surplus cash as expenditures equal earnings. This surplus cash of zero is equivalent to B_H implicitly equaling zero, even though not all cash income generated by the household is necessarily spent as some can be saved. In Eq. (2), if B_H exceeds zero the household has surplus cash, and if B_H equals zero the household has spent all its cash income.
- I_F is *farm income* (USD year^{-1}), and is calculated as the gross value generated from crop and livestock production minus the sum of all variable costs (such as hired labor, fertilizer, seed, and purchased livestock feeds) and fixed costs (such as land and machinery). The variable I_F in Eq. (2) is similar to $p_a(Q_a) - p_hH - p_vV$ using the notation in Eq. (1).
- I_O is *off-farm income* (USD year^{-1}), and is the sum of all family members' earnings from off-farm activities, including salary, income from working on other farms or other part-time jobs, pensions, and remittances. In Eq. (1) if $(L - H - F) < 0$, the household earns off-farm income (see Section 2.2.2), and in our study the household earns off-farm income if $I_O > 0$.
- C_F is *food costs* (USD year^{-1}), and refers to the value of all food consumed by the household, obtained either from the market or from on-farm production, accounting for differences in sales and purchase prices for food.
- C_E is *other expenditures* (USD year^{-1}), i.e. expenditures not related to agriculture (such as electricity, housing, and health care), and is the sum of such expenditures incurred by all family members.

2.2.2. 'Household labor' module

How farm households use their labor time affects multiple livelihood components, including agricultural productivity, on- and off-farm income, and the ability to conduct activities that are not income-earning. The original FarmDESIGN indicator *farm labor balance* did not include off-farm labor conducted by household members. Our study amended FarmDESIGN with a 'Household labor' module to make explicit competing uses of labor for on- and off-farm activities and leisure, as well as the existence of labor markets which facilitate hiring labor onto the farm (Singh et al., 1986; Taylor and Adelman, 2003). We based the 'Household labor' module on the theoretical foundations of the agricultural household (Singh et al., 1986), where the household encounters a time constraint in addition to the cash constraint documented in Eq. (1). In this approach, the household may allocate their total stock of available time (T_T) to on-farm activities related to agricultural production (L_{FA}), off-farm activities (L_{OF}, where $L_{FA} + L_{OF} = F$ from Eq. (1)), or leisure time (T_L), so that:

$$T_T = L_{FA} + L_{OF} + T_L \tag{3}$$

All variables in Eq. (3) are calculated in the 'Household labor' module on a yearly basis (hours year^{-1}) as a sum for all household members. This equation is subject to the constraint that $(T_T - L_{FA} - L_{OF}) \geq 0$, so that $T_L \geq 0$. Leisure refers to all activities that are not captured in L_{FA} and L_{OF}, such as participating in family or community events and holidays. It also can include activities often labelled as non-earning but nevertheless important, including maintaining the home, food preparation, child care, and household and family chores. These activities do not directly contribute to cash income but may affect household wellbeing. The interaction between labor and budget constraints is common in the rural livelihoods literature as a factor shaping farm household decisions (Ellis, 2000). In our study, the 'Household budget' and 'Household labor' modules interact with each other to influence the activities the farm household may undertake given household resources and objectives. If income objectives are important, the household may make resource allocation decisions based on comparing the economic returns to allocate time to on-farm vs. off-farm work, with factors such as agricultural product prices, agricultural productivity, and wage rates all influencing these returns.

An important benefit of the 'Household labor' module compared to the previous 'Farm labor' module used in earlier FarmDESIGN applications is that the competing use of time between on-farm, off-farm, and leisure activities can be included as an objective in the optimization. With output from the new 'Household labor' module, the Labor Use Efficiency (LUE) of different production activities (e.g. cropping patterns) may be also calculated. Here, we calculate LUE as the net USD earned per hectare per hour of input labor, with net USD earned equal to the total value of production minus associated financial costs, following Affholder et al. (2010) and Komarek et al. (2015).

2.2.3. 'Household nutrition' module

The new 'Household nutrition' module facilitates diet quality assessment through proxy indicators for diet diversity, nutrient adequacy, and food availability. Diet quality indicators are recommended for nutrition-sensitive agriculture interventions as a proxy of nutrition, rather than nutrition status indicators (such as stunting and wasting), as diet quality can be directly attributed to agriculture activities via improving the access and consumption of food (McDermott et al., 2015; Herforth & Ballard, 2016). The diet quality indicators in the 'Household nutrition' module are calculated by incorporating availability and consumption of food from both on-farm production and other sources (e.g. purchased, gifts, wild foods). In this study we present and asses only one proxy indicator of dietary quality, *dietary energy deviation*. For a full description of FarmDESIGN's new 'Household nutrition' module and all the metrics it uses, see Groot et al. (2017).

Nutrient deviation metrics calculated in the model compare the theoretical household demand for nutrients to the available nutrient supply from household food production and purchase; actual household dietary intake data is not utilized. Nutritional demands are determined according to standard requirements for healthy individuals, and vary according to age group, sex, and physical state (Institute of Medicine, 2006). The indicator *dietary energy deviation* indicates if the household obtains sufficient energy from its own production and food purchases to meet its energy needs. Here, we estimated the household's dietary energy demand using the recommended dietary allowances (RDA) for the Vietnamese population, assuming a moderate work category (Khan and Hoan, 2008). The dietary energy supply of farm produce allocated to household consumption and purchased foods was calculated based on the energy content for raw foods using a Vietnamese food composition table (SMILING D.5-a, 2013). *Dietary energy deviation* (E_D, expressed as a percentage) is calculated on an annual basis:

$$E_D = \frac{(E_I - E_R)}{E_R} \times 100 \tag{4}$$

where E_I is the household dietary energy intake (kcal) estimated as the total energy supply or contribution from allocations of produced or purchased food to household consumption (household dietary energy supply) and E_R is the household dietary energy requirement (kcal) estimated from the accumulated household RDA (household dietary energy demand). If the value of the indicator *dietary energy deviation* is positive, the modeled farm household exceeds its dietary energy demands by consuming its own production and/or purchased foods. It is important to note that *dietary energy deviation* provides only one dimension (energy) of human nutrition and food security; multiple other aspects of dietary adequacy may be assessed using the full range of metrics in FarmDESIGN's new 'Household nutrition' module.

3. Case study

3.1. Case study area

Part of the larger Central Mekong Area action site, Northwest Vietnam has been the focus of research for development aimed at improving the lives of rural poor through poverty reduction, increased food security, improved nutrition and health, and sustainable natural resource management (ILRI, 2014). Since the beginning of the 21st century, Vietnam has made steady progress towards raising its gross domestic product and reducing poverty at the national scale, yet the incomes of rural households lag behind those in urban areas (Kozel, 2014). Furthermore, Vietnam's malnutrition rate is high among Asian countries despite substantial reduction in the 2000s (GSO, 2016). Northwest Vietnam is a largely rural area where low total farm income, malnutrition, and increased vulnerability of rural poor due to environmental degradation associated with intensified farming practices are prevalent (ILRI, 2014). Within the region, the CGIAR Research Program "Integrated Systems for the Humidtropics" identified the Son La province (Fig. 2) as a high-priority area for addressing these concerns (ILRI, 2014).

3.2. Model farm characterization

The two farms modeled in this study were located in the Doan Ket (21.1444° N, 104.0259° E) and Na Phuong (21.1455° N, 104.0820° E) villages, both in the Mai Son district of Son La province (Fig. 2). A total of 17 farm households were surveyed in Doan Ket and Na Phuong in 2014–2015 as part of the CGIAR Humidtropics project, using the IMPACTLite survey tool (Rufino et al., 2013). This tool was developed to provide a comprehensive yet generic and efficient approach for collecting complex farm characterization data; Rufino et al. (2013) and Silvestri et al. (2014) give a full description of the survey tool and its use, and Douxchamps et al. (2016) provide an example of its application with a link to a complete survey dataset. In Doan Ket and Na Phuong, the survey tool was used to collect baseline data on the biophysical, socio-economic, food intake, and managerial aspects of each of the surveyed farm households during semi-structured interviews. As a supplement to the survey, focus group discussions were held to collect data on food consumption at the household level using food frequency questionnaires and 24-h recalls; these data were used primarily to determine the quantity and cost of food purchased by the household off-farm.

From the 17 surveyed farm households, we selected one from each village with which to conduct the modeling exercise. These were purposefully chosen because their farm lay-out, cropping patterns, primary cash crops, livestock holdings, and market orientation differed notably from one another, thereby providing an opportunity to investigate potential differences in how the improved model would optimize various objectives. Using the survey data, we built a model version of each farm household in FarmDESIGN (Fig. 3). It is important to note that the modeled farms are not spatially explicit. FarmDESIGN cannot reflect, for example, that fruit trees are scattered around a farm; instead, it groups the trees together and treats them as a single production activity, as represented in the farm schematics in Fig. 3.

The farm household selected in Doan Ket (DK) practiced a diverse array of agricultural land uses, cultivating vegetables, mixed fruit trees, coffee, and maize. This household also maintained an aquaculture pond, a home garden, and raised pigs for meat. Close to a main highway, DK had good access to markets for selling commercial crops (primarily vegetables) directly to consumers and wholesalers. In addition to their own production, DK purchased a wide variety of foods from the market, including meat, milk, eggs, fruits, vegetables, rice, and legumes. DK achieved relatively high yields but also incurred large farm input (e.g. seeds, agrochemicals) and household food costs. The farm household selected in Na Phuong (NP) was less diverse in its production strategy, cultivating two main crops: upland maize (one crop per year) and lowland rice (two crops per year). Maize was the chief cash crop, sold primarily to wholesalers as animal feed. Rice, a priority staple food, was kept exclusively for household consumption. NP also kept a variety of livestock, cultivated a small area of coffee and fruit trees, and maintained a home garden. The NP farm household purchased fewer food items from the market, mainly supplementing their own production with purchased rice and meat. Details on the destination (i.e. to home consumption, livestock, or market) of each crop produced on both farms are in the Appendix, Table A1.

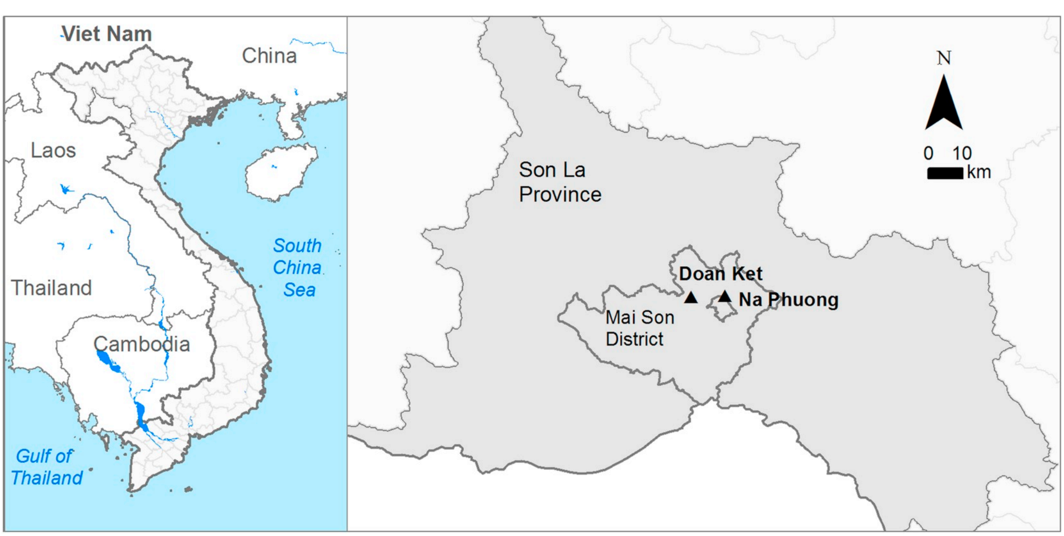

Fig. 2. Location of the case study farms: Doan Ket and Na Phuong villages, Mai Son District, Son La Province, Northwest Vietnam.

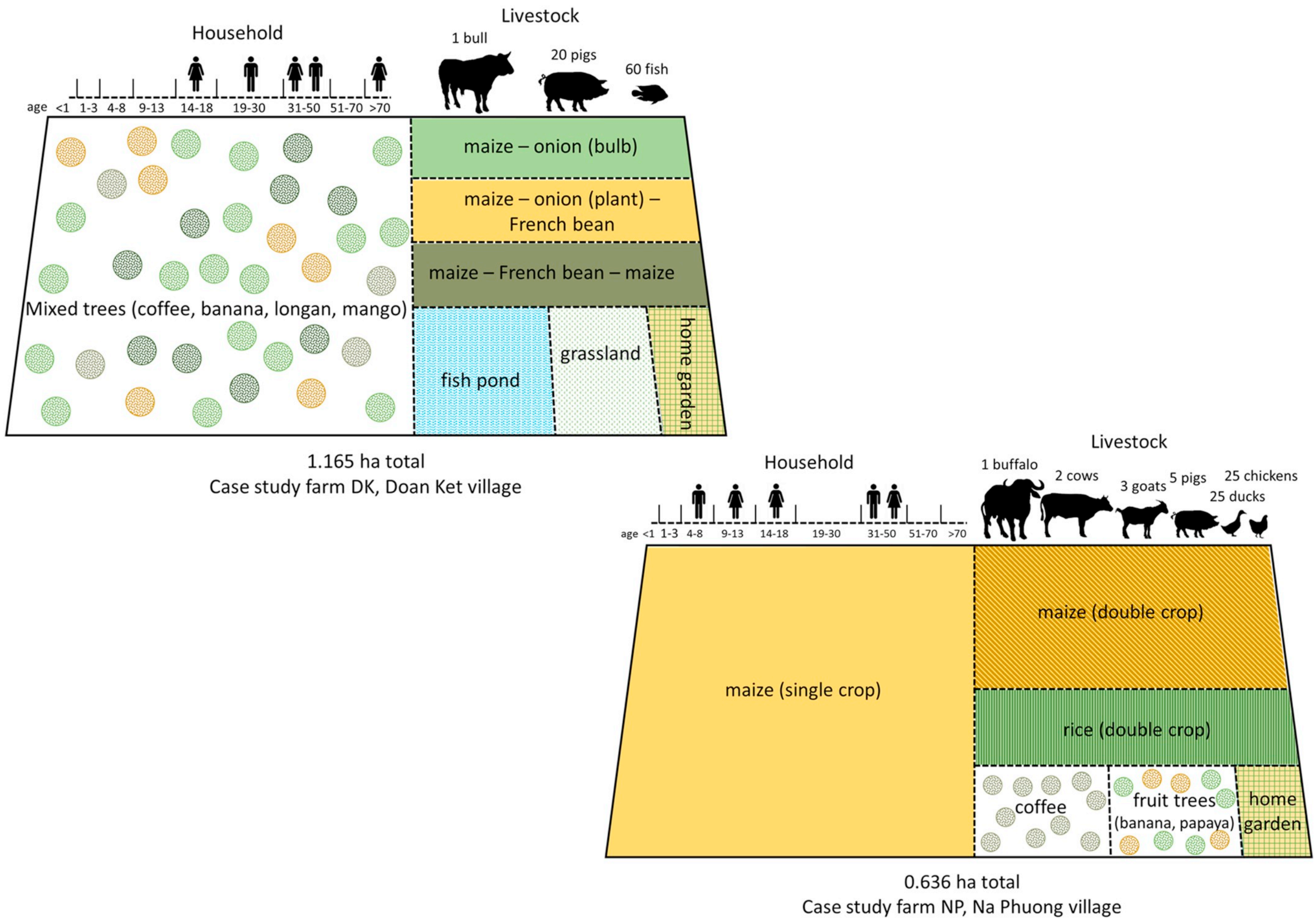

Fig. 3. Stylized representation of the farm households DK and NP modeled in FarmDESIGN. Here we have visualized the modeled version of farm layout as relative crop areas—these are not actual farm field maps, and the schematic is not to scale.

3.3. Model exploration

Before conducting the optimization, we evaluated the current performance of the case study farm households by assessing environmental, social, nutritional, and economic indicators calculated by FarmDESIGN (Table 1). We then used the original configurations of the two farm households as the starting point for the optimization. We examined the model's response to simultaneously optimizing four indicators: maximizing (i) *soil OM balance,*[4] (ii) *household free budget*, (iii) *leisure time*, and (iv) *dietary energy deviation* (Table 1). These objectives were selected on the basis of farm diagnoses conducted during the aforementioned household surveys, and correspond to generally accepted pillars of sustainable development that focus on the environment, society, and economy (Griggs et al., 2013).

We ran the optimization for 1000 iterations on each farm household to ensure stable outcomes, using a mutation probability and mutation amplitude of 0.85 and 0.15, respectively, as parameters for the Differential Evolution algorithm employed in the optimization, as recommended by Groot et al. (2007). The decision variables and constraints set for the multi-objective optimization can be viewed in the Appendix (Tables A2 and A3). Other parameters were set according to the survey data (see Appendix, Table A4), and those unavailable locally were set according to similar studies (Cortez-Arriola et al., 2016; Flores-Sanchez et al., 2015; Groot et al., 2012). When analyzing the model results, we examined trends in how the model allocated crop land, labor, and cash to approach the different objectives, as well as the trade-offs and synergies between objectives (Groot and Rossing, 2011; Groot et al., 2009), rather than the absolute values of the indicators of specific solutions.

Allowing the model to expand and contract the areas of different cropping patterns on each farm by setting these areas as decision variables is a key driver of the alternative farm configurations generated by the model during the optimization. Ideally, the area a certain cropping pattern may be expanded should be constrained by the actual area of suitable land available. For example, in both Doan Ket and Na Phuong, rice is customarily grown in the lowlands where fields are flat and can be flooded, whereas maize is usually grown in the uplands and sown directly into the slope. Consequently, it is not always feasible to treat rice and maize fields as interchangeable in the model. Similarly, coffee is usually grown on hilly land, whereas vegetable crops are more often sown on flat fields, so these two crop areas are also not necessarily interchangeable. In this study we modeled actual farms which *did* have rice growing in the uplands (NP) and coffee growing on flat fields (DK) due to the specifics of these farmers' land holdings and resources, however this is not necessarily the norm. It should therefore be kept in mind that the model results presented here are not necessarily generalizeable to the study area as a whole.

[4] *Soil OM balance* is quantified in FarmDESIGN as the difference between OM accumulation and loss (Groot et al., 2012). Additions of OM are generated by roots and stubble that remain on the field after harvest, green manures and mulches (incorporated into the soil), livestock feed losses (dependent on the feeding system and type of feed supplied), and manure (produced on-farm or imported from an external source).

Table 1
Modeled current environmental, social, nutritional, and economic indicators for farms DK and NP from Doan Ket and Na Phuong villages, respectively. The farm household performance indicators shaded in grey were selected as objectives to maximize during the optimization.

Category	Indicators	DK	NP
Environmental	Soil OM balance (kg ha^{-1} year^{-1})	0	0
	Nitrogen soil losses (kg ha^{-1} year^{-1})	237	333
	Phosphorus soil losses (kg ha^{-1} year^{-1})	74	27
	Potassium soil losses (kg ha^{-1} year^{-1})	145	490
Social	Total on-farm labor required (hr year^{-1})	5377	5830
	Total off-farm labor performed (hr year^{-1})	320	400
	Hired labor (hr year^{-1})	0	0
	Leisure time (hr year^{-1})	76	116
Nutritional	Dietary energy deviation (%)	11.96	0.66
	Proportion of food costs in total expenditures	0.71	0.73
Economic	Farm net income (USD year^{-1})	5302	3023
	Off-farm income (USD year^{-1})	242	332
	Costs for food (USD year^{-1})	1988	3356
	Costs for hired labor (USD year^{-1})	0	0
	Other expenditures (USD year^{-1})	831	438
	Household free budget (USD year^{-1})	2725	1750

Notes: 1 USD = 22,712.13 Vietnamese Dong (VND) (November 21, 2017).

4. Results

4.1. Current farm household performance

Based on current configurations, DK outperformed NP on two of the indicators of interest, *dietary energy deviation* and *household free budget* (Table 1). NP, however, had more *leisure time*. For both farms, the amount of leisure time was relatively low; when spread over a year and assuming an 8-h work day, it ranged from 9.5 days without farm or off-farm work for DK and 14.5 days for NP. On farm DK, the maize—French bean—maize rotation (crop pattern DK4) had the highest LUE, and the home garden (DK5) had the lowest (Table 2); this was because the home garden required daily labor for maintenance and harvesting, while the value of produce was similar to that of pattern DK4. For NP, the highest LUE was achieved in the fruit trees area (NP6), and it was lowest for coffee (NP4). Although both fruit trees and coffee are perennial cropping systems, the NP household reported that managing fruit trees required substantially less labor compared to coffee, provided relatively high value products, and had minimal maintenance costs, making fruit trees the more profitable investment with a high return to labor. Comparing the LUE of double cropped maize (NP1) to double cropped rice (NP3) on NP, the model simulation suggested that growing maize was more efficient than rice in terms of returns to labor. Despite lower cultivation costs, rice required more labor and was of lower cash value than maize.

4.2. Optimization results

The results of the multi-objective optimization revealed similar trade-offs on both farms: (i) between *OM balance* and *household free budget* (Fig. 4a), (ii) between *leisure time* and *household free budget* (Fig. 4b), (iii) between *leisure time* and *OM balance* (Fig. 4c), and (iv) between *dietary energy deviation* and *leisure time* (Fig. 4f). The relationship between *dietary energy deviation* and *household free budget* differed on the two farms, with a trade-off apparent on NP and a less clear association on DK (Fig. 4d). One synergy was observed, between *dietary energy deviation* and *OM balance* on NP, but there was no apparent synergy between the same objectives on DK (Fig. 4e).

4.2.1. OM balance vs. household free budget

Although the slope of the solution frontier differed for the two farms, the trade-off observed between *OM balance* and *household free budget* (Fig. 4a) could primarily be explained by a shift in the dominant cropping patterns for both farms. For farm DK, higher OM balances were achieved in solutions where more cropland was allocated to coffee + fruit trees (DK1) and maize—spring onion—French bean (DK3), and where the area of maize—French bean—maize (DK4) was substantially reduced (Fig. 5a). The solutions approaching higher OM balances for DK were also characterized by lower hired labor inputs (Fig. 5e), and therefore less of the household budget allocated to the cost of hired labor (Fig. 5i). Despite lower labor costs, the actual monetary value of sales from crop pattern DK1 is less than that of pattern DK4 (Table 2), as the fruit produced in DK1 is consumed primarily on-farm, whereas all French beans (and some maize) are sold to market. Furthermore, the costs of cultivation increase with the expansion of DK1 (Fig. 5i). Combined, these factors result in a situation where the cropping patterns chosen by the model to increase *OM balance* were also those patterns with lower cash inflow and higher expenditures due to cultivation costs. On farm NP, solutions with higher OM balances were approached by reducing the areas of maize (NP1 and NP2) and increasing the area of double crop rice (NP3) (Fig. 6a). While this shift did not notably increase farm-scale cultivation costs and in fact lowered household expenditures overall by reducing the need to purchase rice from the market (Fig. 6i), it was offset by the fact that the maize areas collectively bring in more cash, whereas rice is used for home consumption and earns no profit.

Table 2
Labor-use efficiency (LUE, net USD earned per hectare per hour of input labor) of current cropping patterns on farms DK and NP from Doan Ket and Na Phuong villages, respectively.

	Crop pattern	Crop labor (hr ha^{-1} year^{-1})	Total value (USD ha^{-1})	Total cost (USD ha^{-1})	Net profit (USD ha^{-1})	LUE
	Doan Ket					
DK1	Coffee and fruit trees	547	933	623	310	0.57
DK2	Maize—onion rotation	8626	3879	722	3157	0.37
DK3	Maize—spring onion—French bean rotation	8731	3880	646	3233	0.37
DK4	Maize—French bean—maize rotation	5417	4815	1277	3538	0.65
DK5	Home garden	73,000	5107	0	5107	0.07
	Na Phuong					
NP1	Double crop maize	5914	5411	1128	4283	0.72
NP2	Single crop maize	2624	2721	712	2008	0.77
NP3	Double crop rice	6933	2740	496	2243	0.32
NP4	Coffee	8000	2642	1277	1365	0.17
NP5	Home garden	60,833	14,100	0	14,100	0.23
NP6	Fruit trees	1309	4843	0	4843	3.70

4.2.2. Leisure time vs. household free budget

The main factor explaining the trade-off apparent on both farms between the objectives *leisure time* and *household free budget* (Fig. 4b) was the hired labor input. In their original configurations, neither DK nor NP hired any off-farm laborers (Table 1). To approach the objective of increasing *leisure time*, the model shifted the labor burden from the household to paid off-farm laborers (Figs. 5g and 6g), subsequently causing an increase in the expenditure for hired labor (Figs. 5k and 6k) and an associated decrease in *household free budget* (Fig. 4b). Conversely, in the alternative configurations with the largest *household free budget* improvement, the model allocated the labor needed for managing crops to the farm household members (Figs. 5f and 6f), thus reducing *leisure time* to almost zero (Fig. 4b).

4.2.3. Leisure time vs. OM balance

There was a trade-off between *leisure time* and *OM balance* on both farms (Fig. 4c). It was more clearly observed for NP, where it could be explained by the characteristics of the cropping patterns selected during the model optimization. The cropping patterns selected to increase OM—double crop rice (NP3) and coffee (NP4)—also had the largest labor requirements, indicating that farmers may have to choose between meeting farm-scale ecological goals and household labor constraints.

4.2.4. Dietary energy deviation vs. household free budget

A trade-off between *dietary energy deviation* and *household free budget* (Fig. 4d) could result from clear associations between the two objectives, which were most apparent for NP. No rice was grown on farm DK, so on-farm rice production could not contribute to meeting dietary energy demands based on the RDA for dietary energy demand in a moderate work category. Therefore, to increase *dietary energy deviation* on DK, the model allocated more budget to rice purchased from the market (Fig. 5l). With more of the household's income spent on procuring food, less cash would be made available in the *household free budget*, although this relationship was not clearly illumnated in the model results (Fig. 4d). As rice was grown on farm NP, the area of double crop rice (NP3) was expanded by the model to approach the objective of increasing *dietary energy deviation* (Fig. 6d). To expand the area of rice, the model reduced the area of double cropped maize (NP1), which is a cash crop. By replacing an income-generating crop with a crop grown solely for home consumption, the model results highlight the trade-off between allocating land to crops that increase cash flow versus crops that directly support household dietary energy needs. However, the extra cash brought in by marketable crops could theoretically be used to buy more food, a secondary decision not reflected in the modeled results.

4.2.5. Dietary energy deviation vs. OM balance

The synergy observed between *dietary energy deviation* and *OM balance* on farm NP (Fig. 4e) resulted from the model expanding the area of double crop rice (NP3) at the expense of double crop maize (NP1) to approach both objectives (Fig. 6a and d). While the effective OM contribution of the two crops to the soil is relatively similar, rice straw is used as feed for livestock and therefore stays within the system when manure is returned to the field. Maize residues, on the other hand, are commonly burned and therefore 'lost' from the system. Rice thus serves a dual purpose, being a crop which contributes more to soil OM while also producing a staple food. The relationship between the two objectives was unclear on farm DK.

4.2.6. Dietary energy deviation vs. leisure time

The trade-offs between *dietary energy deviation* and *leisure time* on both farms (Fig. 4f) appeared to be linked through the variable of hired labor. Since no rice was grown on DK, rice would have to be sourced solely via the market to improve *dietary energy deviation*. While there were no clear associations between cropland allocation and either objective for farm DK (Fig. 5c and d), the solutions with more *leisure time* were those in which the model allocated more of the required farm labor to hired workers (Fig. 5g). By allocating more household budget to cover the cost of hired labor, the farm household essentially funds their leisure and routes cash out of the reserve that could be used for buying food. On farm NP, solutions with higher *dietary energy deviation* were reached by expanding the area of rice (NP3) (Fig. 6d). Rice contributes directly to the household's dietary energy needs, but also requires more labor than maize, the crop it replaced, resulting in less *leisure time*. Conversely, solutions with more *leisure time* were characterized by a decreased area of rice (NP3) and an expanded area of maize (NP1) (Fig. 6c). However, looking at the association between labor allocation and *lesiure time* for the same model-generated solutions (Fig. 6g), it is apparent that the gain in *leisure time* had less to do with the reduction of maize area and more to do with the fact that the model transfered more labor to hired workers.

5. Discussion

New priorities have emerged to ensure that the analyses of agricultural systems continue to be relevant to the realities encountered by agricultural households across the globe. These priorities include an emphasis on better understanding the interactions between agriculture and human nutrition, a renewed interest in farm household equity concerns including the importance of competing demands for labor and cash, and unravelling agriculture's role in helping countries attain the Sustainable Development Goals (Antle et al., 2017; Jones et al., 2017a, 2017b; Kanter et al., 2018; Stephens et al., 2018), especially related to the goals of no poverty, zero hunger, and life on the land. The

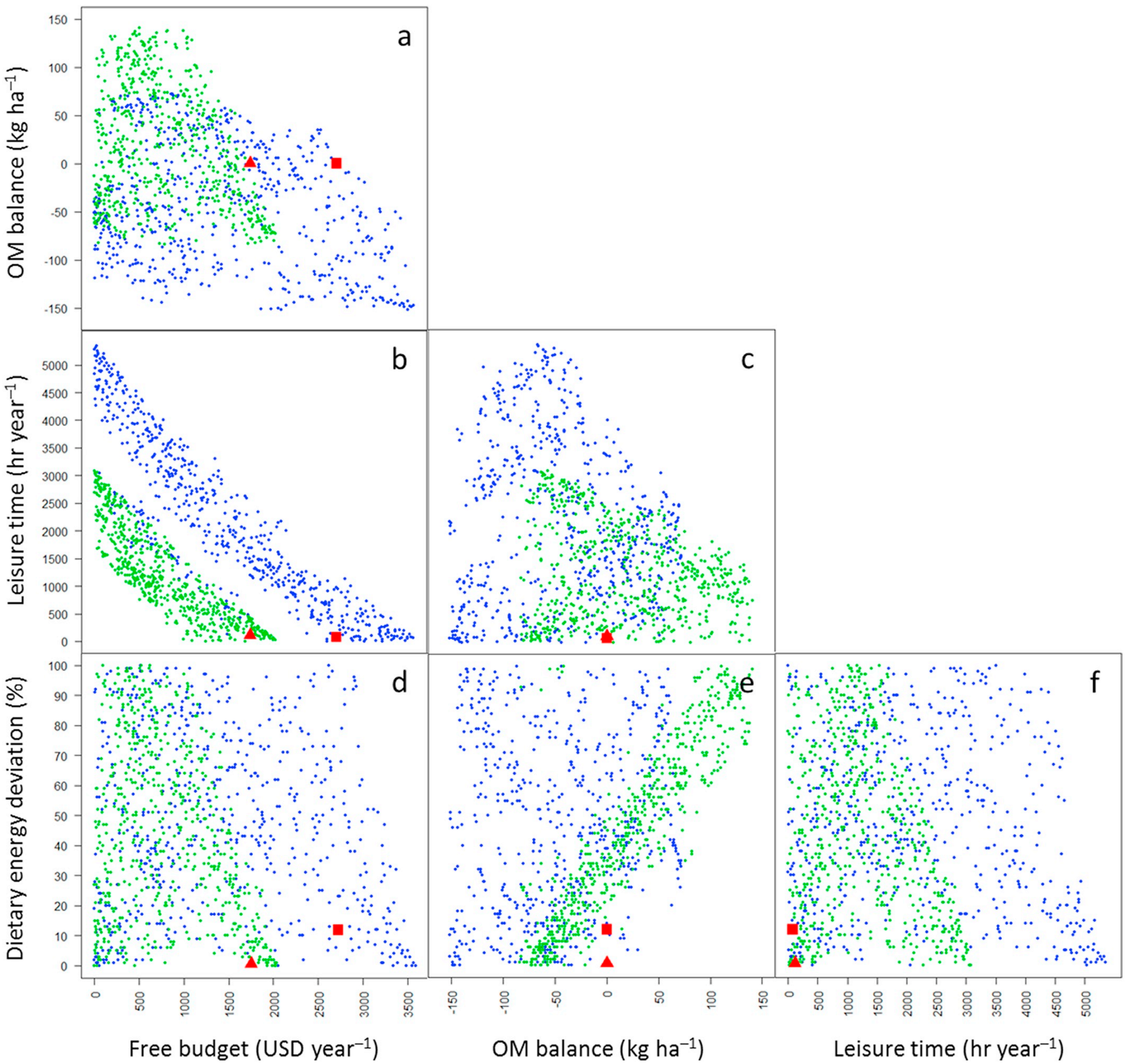

Fig. 4. Relationships between the objectives OM balance, leisure time, household free budget, and dietary energy deviation for farms DK (blue) and NP (green) from Doan Ket and Na Phuong villages, respectively. Each dot indicates an alternative farm configuration. The red symbols (square for DK and triangle for NP) mark the performance of the original farm configuration. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

emergence of new priorities has increased the need for integration among disciplines (for example, human nutrition, economics, and agricultural science), and for the use of case studies employing a systems approach to address the well-being of family farms in terms of income and nutrition while also accounting for competing uses of labor and cash (Antle et al., 2017; Jones et al., 2017a, 2017b). Our study introduces new modules for labor, budget, and nutrition of households in the whole-farm model FarmDESIGN and demonstrates the utility of such a model through an application with two case-study farm households.

Using the expanded FarmDESIGN model with two farm households in Vietnam, we found that the household budget, labor, and nutrition modules extended the model's usefulness by allowing us to identify and explain trade-offs and synergies between resource allocation and farm household objectives. Our results indicated that several trade-offs exist between different household objectives on the two modeled farms, providing a micro-scale perspective into the insights of Kanter et al. (2018), who synthesized trade-offs at multiple spatial scales. These results suggest specific nuances that need considering when examining trade-offs and synergies at the farm–household scale. They also show that interactions between different components of the farm household may affect labor requirements and food availability.

Regarding labor, results suggest trade-offs between *OM balance* and both *leisure time* and *household free budget*. In the case study, some cropping patterns that improved *OM balance* and increased *household free budget* were also those patterns that required more labor. For the NP farm household, replacing maize acreage with rice improved *OM balance*, however maize requires less labor and has a higher LUE (Table 2),

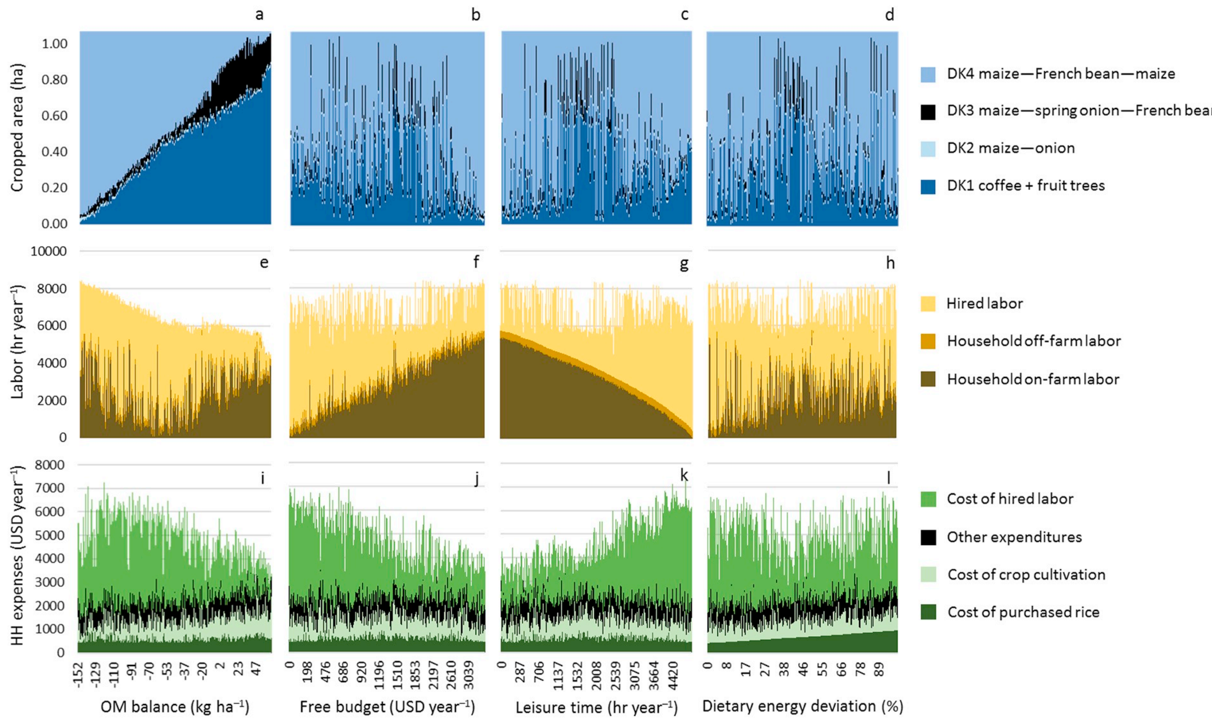

Fig. 5. Modeled allocation of resources (land, labor, money; y axis) in each alternative farm configuration generated to meet the objectives of maximizing organic matter (OM) balance, household free budget, leisure time, and dietary energy deviation (x axis) on farm DK in Doan Ket village, moving from the lowest performing solutions (left) towards the maximum value achieved by the model (right) for each objective.

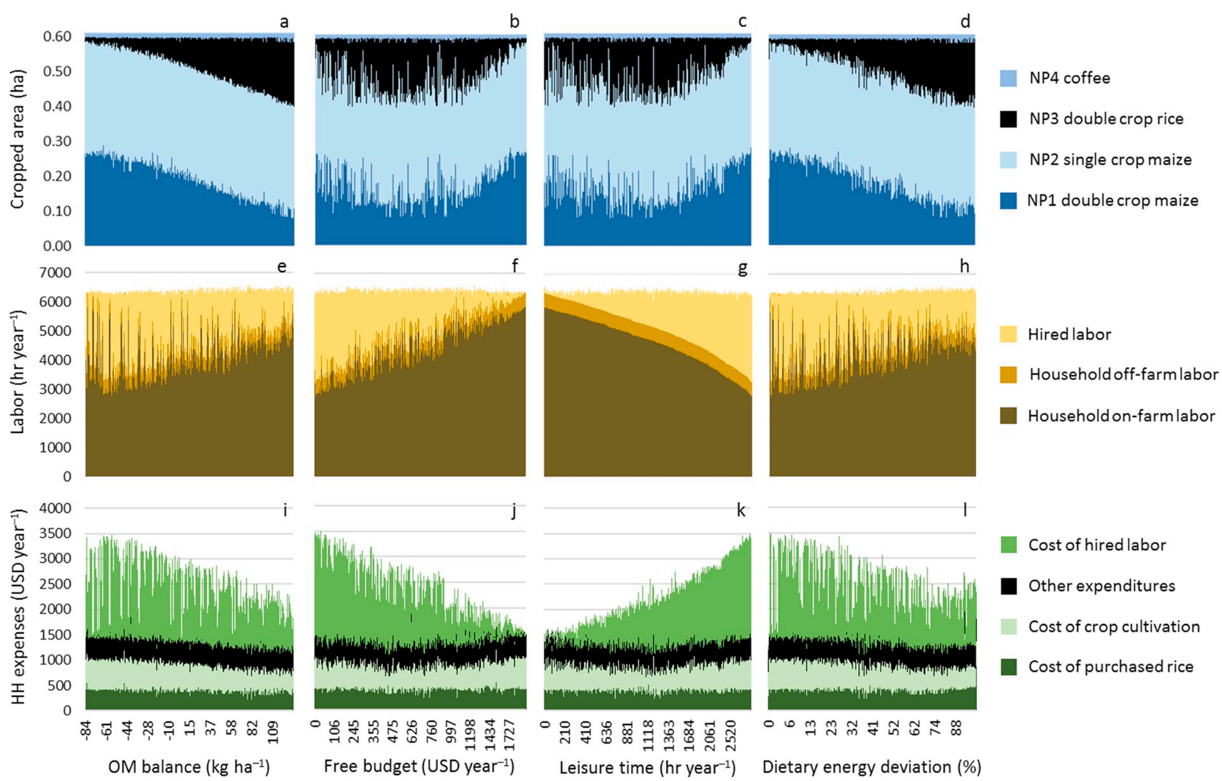

Fig. 6. Modeled allocation of resources (land, labor, money; y axis) in each alternative farm configuration generated to meet the objectives of maximizing organic matter (OM) balance, household free budget, leisure time, and dietary energy deviation (x axis) on farm NP in Na Phuong village, moving from the lowest performing solutions (left) towards the maximum value achieved by the model (right) for each objective.

and as a result on-farm labor allocated to cropping increased as soil organic matter improved. Hiring labor is one option for households to obtain the benefits from the modeled cropping patterns without increasing their labor burden. However, hiring in labor counteracts the financial benefit of expanding the areas of these crops as more of the *household free budget* is allocated to hired labor. Another option to obtain the benefits from these cropping patterns is working more hours off-farm and hiring in labor to compensate; here wage differences between cash earned off-farm and cash paid to laborers may alter the overall *household free budget*, in addition to any search and supervision costs associated with hired labor.

Regarding food availability, trade-offs existed between *dietary energy deviation*, *household free budget*, and *leisure time*. Growing rice to improve *dietary energy deviation* is labor intensive for the NP farm household. Farms that do not grow rice (such as farm household DK) must expand areas of other labor-demanding cash crops to generate sufficient cash to buy rice. This added labor burden must then be taken up by the household, otherwise the increased cash goes to hiring labor instead of buying food, potentially creating a lock-in where an increased labor demand is required to increase food availability. Ultimately, household choices depend on household objectives, preferences, and resource endowments, for example long-term soil quality, reducing the labor burden, or cash flow, each of which may affect quality of life in different ways.

Given that only two specific farm households were modeled, the trends illuminated by the model in this case study are not necessarily representative of farmers' realities throughout the study region and therefore the optimization results should not be treated as directly transferable. As noted in Section 3.3, it may not be realistic to treat all crop areas as interchangeable. In this study we modeled actual farms which did have rice growing in the uplands (NP) and coffee growing on flat fields (DK), due to the farmers' specific landholdings, resources, and innovations, although this was not the norm in the study region. Adopting the cropping configurations suggested by the model to optimize different objectives (for example replacing a maize area with rice) would for most farmers mean taking on the potentially costly and labor-intensive endeavor of transforming less-suitable land to accomodate crops not traditionally grown there. In further studies of this kind, and if extension or policy recommendations are to be designed for the region as a whole based on model results, more generally applicable decision variables and constraints should be set based on farm household typologies, agro-ecological zones, and observed cropping patterns.

Debates exist if trade-offs are ubiquitous in agricultural systems or if win-win situations are possible (Giller et al., 2011). Our results suggest both trade-offs and synergies can occur in agricultural systems, and their nature often depends on household resources and objectives. A similar trade-off to that shown here between social and environmental indicators has been seen in Northern Vietnam (Affholder et al., 2010), where introducing conservation agriculture improved environmental indicators but initially reduced LUE. In Kenya, applying extra mineral fertilizer increased LUE in home gardens but also increased greenhouse gas emissions (Kurgat et al., 2018), highlighting the common occurrence of trade-offs. However, the simulated synergy between *dietary energy deviation* and *OM balance* for the NP farm household growing rice supports arguments that trade-offs between environmental sustainability and human nutrition are not always universal (Fan and Brzeska, 2016). Furthermore, reducing labor demand is not always desirable when viewed from a broader scale. For example, the System of Rice Intensification can improve environmental and economic performance, but the reduced labor demand (compared with conventional rice systems) can reduce wages earned by landless laborers (Gathorne-Hardy et al., 2016). Similarly, a greater allocation of time to leisure can have a negative effect on farm profits because labor is an input into the production process (Taylor and Adelman, 2003), which is also shown here. Our study complements earlier studies, such as Giller et al. (2011), in reinforcing the message that no silver bullets exist in improving farm household livelihoods, rather the analysis of farm-households with modeling tools can help identify baskets of options and best bets.

Our study focused on the Describe, Explain, and Explore phases of the DEED approach. Differences between the structure of the modeled farm households were reflected in the distinct ways the model responded to optimizing different objectives, illustrating that the new modules follow logic and intuition. A more formal model evaluation would strengthen the research. For the FarmDESIGN model the evaluation of its performance in terms of model accuracy and output evaluation is to a large degree straightforward (Groot et al., 2012), since resource flows are derived from measured or estimated quantities of material accumulated in farm components or imported into or exported from the farm. The economic calculations only use reported costs, prices and expenditures.

For the new modules it is crucial to collect accurate data on the household composition and for each of the household members their availability for labor and allocation of time to various activities on the farm, off-farm and the household, and associated revenues. Such data are often hard to obtain in particular for a complete representative year, hence we rely on intensive interactions with farmers in participatory settings and on-farm activities to complement data obtained through surveys. Similar difficulties of data acquisition are faced with respect to food quality and household nutrition. The main uncertainties in the accuracy of model simulations reside in the quality of the input data and in the calculations of feed balance, manure degradation, nutrient losses from manure, and soil organic matter breakdown. These processes are difficult to parameterize, in particular in an on-farm setting. As a consequence, for these process-based aspects of the model output evaluation is dependent on assessments based on farmer and expert knowledge, and comparison of trends with experimental findings (Groot et al., 2012).

A potential future use of the expanded FarmDESIGN model is to consider what specific interventions can help farm households improve their livelihoods within the context of changing market prices, farm family size, and indirect or direct household demands for nutritious foods. A focus here could be on increasing the technical efficiencies of cropping systems in Vietnam, which have scope for improvement (Nguyen, 2017). Increasing technical efficiencies may also entail trade-offs and synergies and the expanded FarmDESIGN model has the potential to better capture these. Examining interventions related to nutrient-rich crops is also relevant, and could take advantage of FarmDESIGN's nutrition module. Implementing these future uses would contribute to the final phase of the DEED cycle (Design) and allow for more generalizable recommendations to be deduced from localized modeling efforts.

6. Conclusions

Family farming households play an important role in global food production. Due to their heavy reliance on family labor, as well as their status as both a producer and consumer, decision-making regarding resource allocation and income distribution should also be considered when seeking to optimize these systems and move towards sustainability goals. Our study introduced and illustrated the application of three new modules ('Household budget', 'Household labor', and 'Household nutrition'), which were added to the FarmDESIGN model. These expand the model's capacity to capture trade-offs and synergies between performance indicators at the farm–household level. This was shown by exploring optimization scenarios for two actual farms in Northwest Vietnam, where we found both ubiquitous trade-offs (e.g. between *leisure time* and *household free budget*) and a potential synergy between environmental and human nutrition indicators. In addition to the specifics of this case study, the expanded model has general appeal for exploring such trade-offs and synergies for other resource-constrained farm households.

The expanded FarmDESIGN model now more closely reflects the centrality of the household in farm management, and therefore serves as a starting point for researchers to simultaneously, and more thoroughly, evaluate the economic, environmental, nutritional, and social performance of farming systems by considering the household perspective. With its improved capabilities, the model may be used to investigate the impact of numerous relevant global change scenarios that directly influence farm households, for example population growth, market price fluctuations, or nutritional security, as well as the impact of interventions targeted to improve livelihoods within such scenarios.

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Appendix A

Table A1
Destination of crop products harvested on farms DK and NP in the original farm configurations.

Product	Consumed at home	Fed to livestock	Sold to market
DK			
Coffee			✓
Banana	✓		
Longan			✓
Mango	✓		
Maize (grain)	✓	✓	
Onion (bulb)	✓		✓
Onion (plant)			✓
French bean			✓
Home garden	✓		
NP			
Coffee			✓
Banana	✓		✓
Papaya	✓		
Maize (grain)		✓	✓
Rice (grain)	✓		
Home garden	✓		

Table A2
Decision variables and constraints set for the optimization routine on farm DK. Decision variables tell the model which parameters may be adjusted with the evolutionary algorithm, and constraints limit farm reconfigurations so that specific indicator values fall between the minimum and maximum.

	Original	Minimum	Maximum
Decision variables			
DK1 coffee and fruit trees area (ha)	0.7	0.01	1
DK2 maize—onion rotation area (ha)	0.1	0.01	1
DK3 maize—spring onion—French bean rotation area (ha)	0.15	0.01	1
DK4 maize—French bean—maize rotation area (ha)	0.12	0.01	1
Pigs (number)	20	18	22
Maize grain fed to animals (kg DM year^{-1})	3137	0	3500
Industrial feed fed to animals (kg DM year^{-1})	2150	2150	3500
Hired regular labor (hr year^{-1})	0	0	∞
HH off-farm labor input (hr year^{-1})	320	0	500
Rice used for home consumption (kg DM year^{-1})	942	0	4000
Constraints			
Farm area (ha)	1.07	1	1.07
DM intake deviation ruminants (%)	−0.95	−999	0
Energy deviation ruminants (%)	4.04	−5	5
DM intake deviation non-ruminants (%)	−71.37	−9999	0
Energy deviation non-ruminants (%)	−4.79	−5	5
N soil losses (kg ha^{-1} year^{-1})	237.13	20	∞
P soil losses (kg ha^{-1} year^{-1})	73.81	0	∞
K soil losses (kg ha^{-1} year^{-1})	144.68	0	∞
Leisure time (hr year^{-1})	76	0	∞
HH free budget (USD year^{-1})	2725	0	∞
Dietary energy deviation (%)	12	0	100

Notes: HH = household. 1 USD = 22,712.13 Vietnamese Dong (VND) (November 21, 2017).

Table A3
Decision variables and constraints set for the optimization routine on farm NP. Decision variables tell the model which parameters may be adjusted with the evolutionary algorithm, and constraints limit farm reconfigurations so that specific indicator values fall between the minimum and maximum.

	Original	Minimum	Maximum
Decision variables			
NP1 maize—maize rotation area (ha)	0.15	0.01	0.6
NP2 single crop maize area (ha)	0.35	0.01	0.6
NP3 rice—rice rotation area (ha)	0.09	0.01	0.6
NP4 coffee area (ha)	0.02	0.01	0.6
Pigs (number)	5	3	7
Industrial feed fed to animals (kg DM $year^{-1}$)	516	516	1000
Rice straw, fraction non grazing	0.7	0	0.7
Young maize (whole plant) fraction non grazing	0.8	0	0.8
Wild grass to animals (kg)	6000	4000	6500
Wild grass fraction non grazing	0.12	0	0.12
Hired regular labor (hr $year^{-1}$)	0	0	∞
HH off-farm labor input (hr $year^{-1}$)	400	0	500
Rice used for home consumption (kg DM $year^{-1}$)	361	0	4000
Constraints			
Farm area (ha)	0.636	0.6	0.636
DM intake deviation, grazing period (%)	−12.48	−999	0
Energy deviation, grazing period (%)	−3.24	−5	5
DM intake deviation, non-grazing period (%)	−27.74	−999	0
Energy deviation, non-grazing period (%)	−4.35	−5	5
N soil losses (kg ha^{-1} $year^{-1}$)	336.86	20	∞
P soil losses (kg ha^{-1} $year^{-1}$)	27	0	∞
K soil losses (kg ha^{-1} $year^{-1}$)	490.32	0	∞
Leisure time (hr $year^{-1}$)	116	0	∞
HH free budget (USD $year^{-1}$)	1750	0	∞
Dietary energy deviation (%)	0.66	0	100

Notes: HH = household. 1 USD = 22,712.13 Vietnamese Dong (VND) (November 21, 2017).

Table A4
Model parameters relating to the sale and purchase prices of farm goods, set to the local conditions of the Vietnam case study.

Model parameter	DK	NP
Labor (USD hr^{-1})		
Hired labor wage paid; parameter p_w in Eq. (1)	0.66	0.66
Off-farm wage earned; parameter p_h in Eq. (1)	0.76	0.83
Crops sold (sale price, fresh weight) (USD kg^{-1}); vector p_a in Eq. (1)		
Rice grain	NA	0.31
Maize grain	0.26	0.25
Onion (bulb)	0.22	NA
Spring onion (plant)	0.13	NA
French bean	0.26	NA
Coffee	0.51	0.44
Banana fruit	0.14	0.18
Longan fruit	0.44	NA
Mango fruit	0.44	NA
Purchased food (market price, fresh weight) (USD kg^{-1}); vector p_m in Eq. (1)		
Rice grain	0.53	0.53
Bamboo shoot	0.44	NA
Black bean	1.98	NA
Carrot	0.33	NA
Green mung bean	1.76	NA
Orange	1.54	NA
Peanut	2.20	NA
Pumpkin	0.33	NA
Tomato	0.22	NA
Watermelon	0.66	NA
Fertilizers (market price) (USD kg^{-1}); vector p_v in Eq. (1)		
K	NA	0.34
NPK 13N $13P_2O_5$ $13K_2O$	0.20	0.20
NPK 8N 12 P_2O_5 12 K_2O	0.66	NA
Urea	0.40	0.42

Notes: 1 USD = 22,712.13 Vietnamese Dong (VND) (November 21, 2017).

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